VII International Conference on Computational Methods in Marine Engineering
MARINE 2017
M. Visonneau, P. Queutey and D. Le Touzé (Eds)

SYSTEM-BASED MANEUVERING SIMULATION OF A SHIP NAVIGATING IN THE CONFINED WATERWAY

P. DU*, A. OUAHSINE*, P. SERGENT†

* Laboratoire Roberval, UMR-CNRS 7337
Sorbonne Universités, Université de Technology de Compiègne
Centre de Recherches Royallieu, CS 60319, 60203 Compiègne cedex, France
e-mail: pp1565156@126.com (P. Du); ouahsine@utc.fr (A. Ouahsine)

† CEREMA-134, rue de Beauvais, CS 60039, 60200 Compiègne, France

Key words: Maneuvering, confined waterway, bank effect, trajectory

Abstract. The system-based maneuvering simulations were conducted to investigate the ship navigating in the confined waterway. The confinement effect was included using the model of Vantorre [1]. The maneuvering model was validated using the turning circle and zigzag tests, and the confinement model was verified using the experimental data of Norrbin [2]. The good agreement proved the validity of our method. Using this method, the influences of the ship-bank distance and the propeller rate of turn were studied and concluded. Small ship-bank distance and large propulsion were proved to enhance the confinement effect.

1 INTRODUCTION

When a ship is maneuvered in a confined waterway, its motion will be influenced by the channel bank and bottom [3, 4, 5, 6]. These effects will change the maneuverability of the ship and may cause marine accidents if not controlled well. In this paper, system-based maneuvering simulations are conducted for an Esso Bernicia 190,000 DWT tanker in a confined waterway. A non-linear maneuvering model is adopted and the confinement effect is included based on the model of Vantorre [1]. The maneuvering model is verified using the turning circle and zigzag tests [7]. The confinement model is validated using the experimental data of Norrbin [2].

2 METHODOLOGIES

The maneuvering equations in 3-DOF (degrees of freedom) can be written as (Fig.1) [8]:

$$\begin{aligned} \dot{u} - vr - x_G r^2 &= gX'' \\ \dot{v} + ur + x_G r^2 &= gY'' \\ \left(Lk_z''\right)^2 \dot{r} + x_G(\dot{v} + ur) &= gLN'' \end{aligned} \tag{1}$$

where u and v are the surge and sway velocities, $\dot{u}$ and $\dot{v}$ are the surge and sway accelerations, r and $\dot{r}$ are the yaw rate and yaw acceleration respectively, g is the gravitational acceleration, G is the gravity center of the ship, O is the midship point, L is the ship length between perpendiculars, x_G is the position of the gravity center in OX-direction. $k''_z = \frac{1}{L}\sqrt{\frac{I_z}{m}}$ is the non-dimensional radius of turning, where I_z is the inertial moment of a ship with respect to OZ-axis. $X'' = X/(mg), Y'' = Y/(mg), N'' = N/(mgL)$ are the non-dimensional forces and moment.

For the Esso Bernicia 190,000 DWT tanker, the non-dimensional equations for surge, sway and yaw dynamics are:

$$\begin{aligned} gX'' &= X''_{\dot{u}}\dot{u} + \tfrac{1}{L}X''_{u|u|}u\,|u| + X''_{vr}vr + \tfrac{1}{L}X''_{v|v|}v\,|v| \\ &+\tfrac{1}{L}X''_{c|c|\delta\delta}c\,|c|\,\delta^2 + \tfrac{1}{L}X''_{c|c|\beta\delta}c\,|c|\,\beta\delta + gT''\,(1-t_d) \\ &+X''_{\dot{u}\xi}\dot{u}\xi + \tfrac{1}{L}X''_{|u|u\xi}\,|u|\,u\xi + X''_{vr\xi}vr\xi + \tfrac{1}{L}X''_{vv\xi\xi}v^2\xi^2 \end{aligned} \tag{2}$$

$$\begin{aligned} gY'' &= Y''_{\dot{v}}\dot{v} + \tfrac{1}{L}Y''_{uv}uv + \tfrac{1}{L}Y''_{|v|v}\,|v|\,v + \tfrac{1}{L}Y''_{|c|c\delta}\,|c|\,c\delta + Y''_{ur}ur \\ &+\tfrac{1}{L}Y''_{|c|c|\beta|\beta|\delta|}\,|c|\,c\,|\beta|\,\beta\,|\delta| + Y''_{T}gT'' + Y''_{ur\xi}ur\xi + \tfrac{1}{L}Y''_{uv\xi}uv\xi \\ &+Y''_{\dot{v}\xi}\dot{v}\xi + \tfrac{1}{L}Y''_{|v|v\xi}\,|v|\,v\xi + \tfrac{1}{L}Y''_{|c|c|\beta|\beta|\delta|\xi}\,|c|\,c\,|\beta|\,\beta\,|\delta|\,\xi \end{aligned} \tag{3}$$

$$\begin{aligned} gLN'' &= L^2N''_{\dot{r}}\dot{r} + N''_{uv}uv + LN''_{|v|r}\,|v|\,r + N''_{|c|c\delta}\,|c|\,c\delta + LN''_{ur}ur \\ &+N''_{|c|c|\beta|\beta|\delta|}\,|c|\,c\,|\beta|\,\beta\,|\delta| + N''_{T}gT'' + LN''_{ur\xi}ur\xi + L^2N''_{\dot{r}\xi}\dot{r}\xi \\ &+N''_{uv\xi}uv\xi + LN''_{|v|r\xi}\,|v|\,r\xi + N''_{|c|c|\beta|\beta|\delta|\xi}\,|c|\,c\,|\beta|\,\beta\,|\delta|\,\xi \end{aligned} \tag{4}$$

where $X''_{\dot{u}}, X''_{u|u|}, ..., Y''_{\dot{v}}, Y''_{uv}, ..., N''_{\dot{r}}, N''_{uv}, ..., N''_{|c|c|\beta|\beta|\delta|\xi}$ are the non-dimensional derivatives of ship hydrodynamic coefficients. δ is the rudder angle, t_d is the thrust deduction coefficient. $\beta = arctan(-v/u)$ is the drift angle. $\xi = T_d/(h - T_d)$, where h is the water depth, T_d is the ship draft. T'' is the non-dimensional propeller thrust given by:

$$T'' = \frac{1}{gL}T''_{uu}u^2 + \frac{1}{g}T''_{un}un + \frac{L}{g}T''_{|n|n}|n|n \tag{5}$$

where T_{uu}, T_{un} and $T_{|n|n}$ are the hydrodynamic coefficients of the propeller, n is the shaft velocity. c is the flow velocity at the rudder estimated by:

$$c^2 = c_{un}un + c_{nn}n^2 \tag{6}$$

where c_{un} and c_{nn} are the hydrodynamic coefficients of the rudder.

The confinement effect is included as external forces and moments acted on the ship hull into the non-dimensional ship maneuvering equations. Then Eq.1 becomes:

$$\begin{aligned} \dot{u} - vr - x_G r^2 &= gX'' + gX''_B \\ \dot{v} + ur + x_G\dot{r} &= gY'' + gY''_B \\ (Lk''_z)^2\,\dot{r} + x_G(\dot{v} + ur) &= gLN'' + gLN''_B \end{aligned} \tag{7}$$

where X''_B, Y''_B and N''_B are non-dimensional forces and moment of the ship-bank/bottom interaction (Fig.2). According to [1], they can be decomposed as:

$$\begin{aligned} X_B &\approx 0 \\ Y_B &= Y_B^H + Y_B^P + Y_B^{HP} \\ N_B &= N_B^H + N_B^P + N_B^{HP} \end{aligned} \tag{8}$$

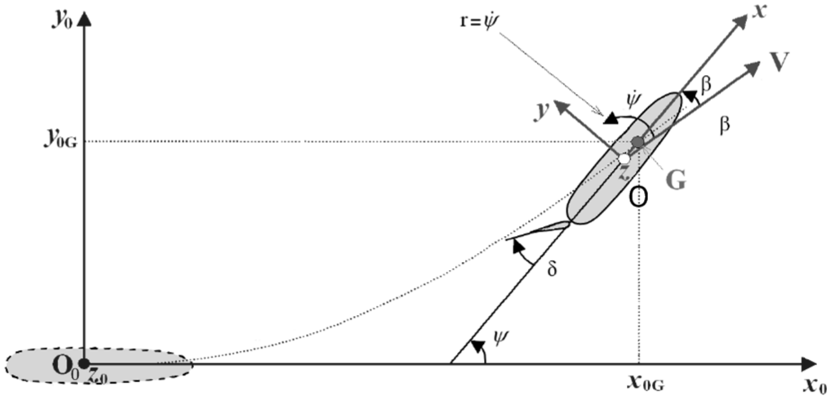

Figure 1: Coordinate system in the ship maneuvering analysis

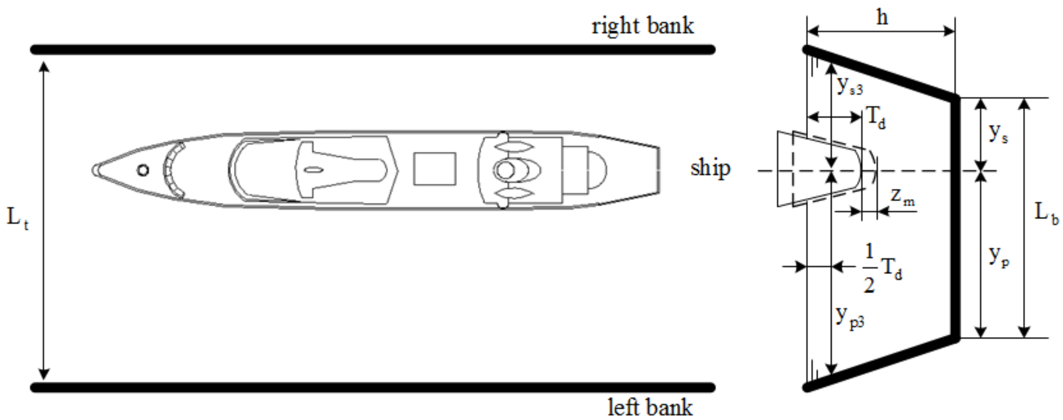

Figure 2: Parameter definitions of a ship in the confined waterway

where Y_B^H, N_B^H are the effects of the forward speed, Y_B^P, N_B^P are the effects of the ship propulsion, Y_B^{HP}, N_B^{HP} are the coupled effects of the forward speed and propulsion.

$$Y_B^H = \frac{1}{2}\rho L T_d u^2 \sum_{i=1}^{2}\sum_{k=0}^{2} \alpha_{ik}^H y_B^i \left(\frac{T_d}{h_{eff} - T_d}\right)^k \tag{9}$$

$$N_B^H = \frac{1}{2}\rho L^2 T_d u^2 \sum_{i=1}^{2}\sum_{k=0}^{2} \beta_{ik}^H y_B^i \left(\frac{T_d}{h_{eff} - T_d}\right)^k \tag{10}$$

$$Y_B^P = \frac{1}{2}\rho L T_d V_T^2 \sum_{i=1}^{2}\sum_{k=0}^{2} \alpha_{ik}^P y_{B3}^i \left(\frac{T_d}{h_{eff} - T_d}\right)^k \tag{11}$$

$$N_B^P = \frac{1}{2}\rho L^2 T_d V_T^2 \sum_{i=1}^{2}\sum_{k=0}^{2} \beta_{ik}^P y_{B3}^i \left(\frac{T_d}{h_{eff} - T_d}\right)^k \tag{12}$$

Geometrical parameters	Values
L	304.8 (m)
B	47.17 (m)
T_d	18.46 (m)
∇ (displacement)	220000 (m^3)
L/B	6.46
B/T_d	2.56
C_B (block coefficient)	0.83
U_0 (design speed)	16 $(knots)$
n (propeller rate of turn)	80 (rpm)

Table 1: Geometrical parameters of the Esso Bernicia 190,000 DWT tanker

$$Y_B^{HP} = \frac{1}{2}\rho L T_d V_T^2 F_r \sum_{i=1}^{2}\sum_{k=0}^{2}\alpha_{ik}^{HP} y_{B3}^i \left(\frac{T_d}{h_{eff} - T_d}\right)^k \tag{13}$$

$$N_B^{HP} = \frac{1}{2}\rho L^2 T_d V_T^2 F_r \sum_{i=1}^{2}\sum_{k=0}^{2}\beta_{ik}^{HP} y_{B3}^i \left(\frac{T_d}{h_{eff} - T_d}\right)^k \tag{14}$$

where α_{ik}^H, β_{ik}^H, α_{ik}^P, β_{ik}^P, α_{ik}^{HP}, β_{ik}^{HP} are the regression coefficients, which can refer to the work of Vantorre [1]. The reference velocity V_T is introduced as:

$$V_T = \sqrt{\left|\frac{T}{\frac{1}{8}\rho\pi D^2}\right|} \tag{15}$$

where T is the propeller thrust, D is the propeller diameter, ρ is the water density. y_B and y_{B3} are non-dimensional quantities defined by:

$$y_B = \frac{1}{2}B\left(\frac{1}{y_p} + \frac{1}{y_s}\right) \tag{16}$$

$$y_{B3} = \frac{1}{2}B\left(\frac{1}{y_{p3}} + \frac{1}{y_{s3}}\right) \tag{17}$$

where y_p and y_{p3} are the distances from the ship center to the bank on the port side (Fig.2), y_s and y_{s3} are those on the starboard side, B is the breadth of the ship. h_{eff} is the effective depth of the channel:

$$h_{eff} = h - z_m \tag{18}$$

where h is the water depth, z_m is the average sinkage due to the squat effect.

3 MANEUVERING MODEL TESTS

This work uses the Esso Bernicia 190,000 DWT tanker, whose parameters are given in Tab.1. There are 34 hydrodynamic coefficients in the maneuvering equations (2-4), whose values are given in Tab.2. Here the hydrodynamics are optimized using the procedures in [8].

No.	Hydrodynamic coefficients	Values	No.	Hydrodynamic coefficients	Values
1	$X''_{\dot{u}}$	-0.0500	18	$Y''_{\|v\|v\xi}$	-1.5000
2	X''_{vr}	1.0200	19	$N''_{vr\xi}$	-0.1200
3	$Y''_{\dot{v}}$	-0.0200	20	$Y''_{\|c\|c\delta}$	0.1794
4	$Y''_{\|c\|c\|\beta\|\beta\|\delta\|}$	-2.1600	21	$Y''_{uv\xi}$	0.0000
5	Y''_{T}	0.0500	22	$N''_{uv\xi}$	-0.2043
6	N''_{T}	-0.0240	23	$X''_{c\|c\|\beta\delta}$	0.1220
7	$N''_{\dot{r}}$	-0.0608	24	$N''_{\|c\|c\delta}$	-0.0883
8	$Y''_{\|v\|v}$	-2.4000	25	$X''_{vv\xi\xi}$	0.0125
9	$N''_{\|v\|r}$	-0.3000	26	$N''_{\|c\|c\|\beta\|\beta\|\delta\|}$	0.6880
10	$X''_{\|v\|v}$	0.3000	27	$Y''_{\|c\|c\|\beta\|\beta\|\delta\|\xi}$	-0.1910
11	Y''_{uv}	-1.2050	28	$N''_{\|c\|c\|\beta\|\beta\|\delta\|\xi}$	0.3440
12	N''_{uv}	-0.4510	29	Y''_{ur}	0.2480
13	$X''_{\dot{u}\xi}$	-0.0500	30	N''_{ur}	-0.1717
14	$Y''_{\dot{v}\xi}$	-0.3780	31	$X''_{u\|u\|}$	-0.0312
15	$Y''_{ur\xi}$	0.1420	32	$N''_{\dot{r}\xi}$	-0.0054
16	$N''_{ur\xi}$	-0.0448	33	$X''_{\|u\|u\xi}$	-0.0050
17	$X''_{vr\xi}$	0.3780	34	$X''_{c\|c\|\delta\delta}$	-0.0984

Table 2: Hydrodynamic coefficients of the Esso Bernicia 190,000 DWT tanker

The maneuvering model here is validated using the turning circle and zigzag tests. As shown in Figs.(3-4), the trajectory and heading angle correspond well with the experimental data. Thereby this model can be further used to implement the ship-bank/bottom interaction in the confined waterway.

4 SHIP MANEUVERING IN A CONFINED WATERWAY

Based on the maneuvering equations 7, the ship navigating in the confined waterway can be simulated. The experimental results of Norrbin [2] are selected for validation. The setups can be seen in Tab.3. As shown in Fig.5, our simulations correspond well with the experimental data.

Two cases are further carried out to consider the influences of the ship-bank distance and the propeller rate of turn (Tab.3). As shown in Fig.6, when the ship is closer to the bank, the bank effect will become more obvious and the ship will deviate more from the bank. In Fig.7, when the propeller revolution increases, according to the equations 9-14, the forces and moment induced by the confinement effect will also increase. So greater propulsion will make the ship turn more to the middle of the channel. Overall, small ship-bank distance and large propeller rate of turn will enhance the confinement effect when a ship is maneuvered in the confine waterway.

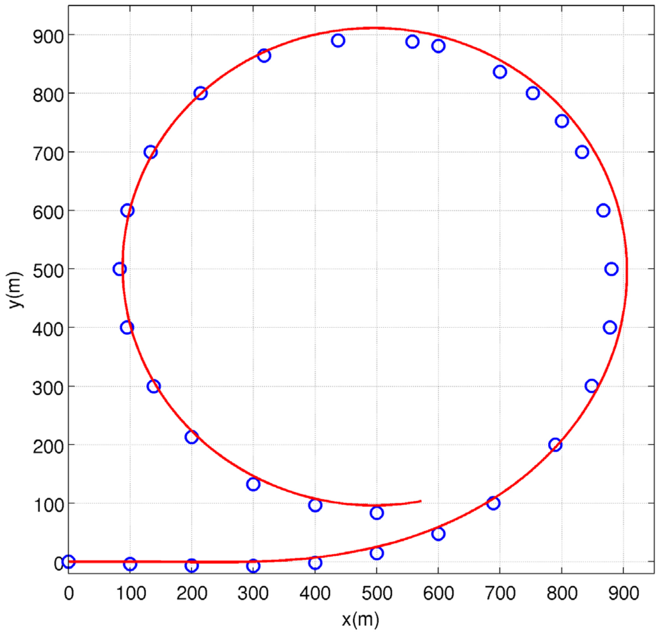

Figure 3: Ship trajectories in the turning circle test. '∘': experimental result [7]; '-': simulation result.

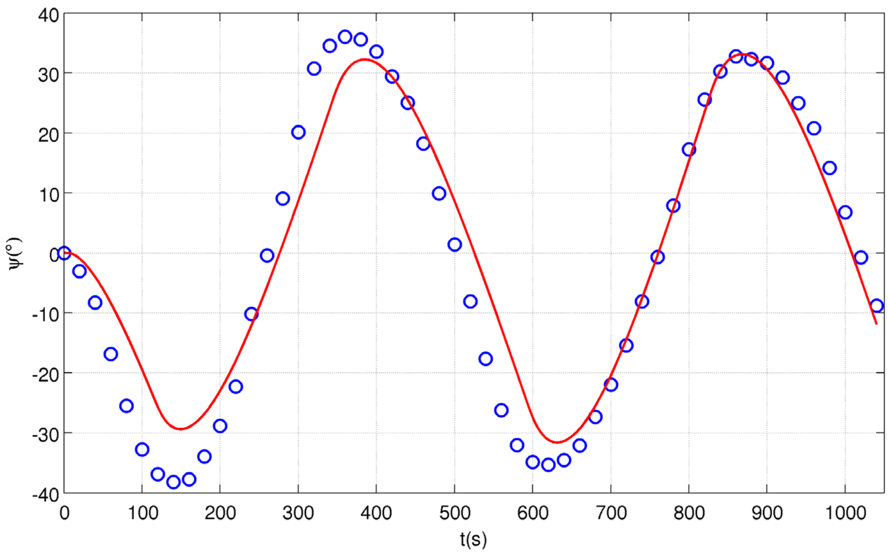

Figure 4: Yaw angles in the zigzag test. '∘': experimental result [7]; '-': simulation result.

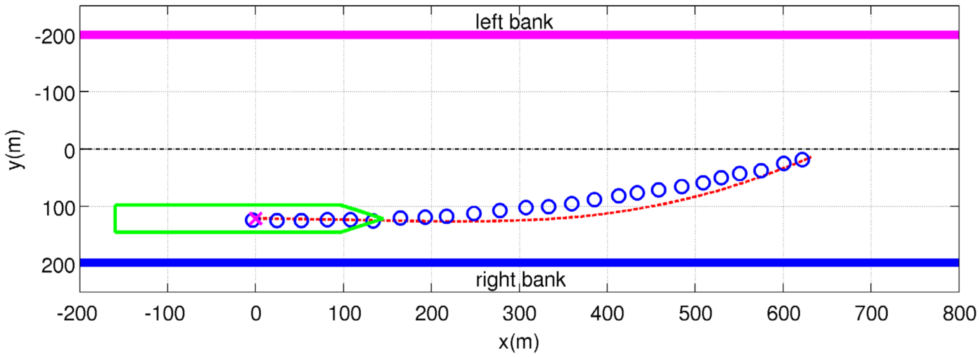

Figure 5: Trajectory of the ship navigating in the confined waterway (validation). '○': experimental result [2]; '−−': simulation result.

Parameters	Validation	Case 1	Case 2
L_b (width of channel bottom) $[m]$	300	300	300
L_t (width of channel top) $[m]$	305	453	453
Channel slope of both sides	10:1	1:3	1:3
h (water depth) $[m]$	25.5	25.5	25.5
T_d (draft) $[m]$	18.46	18.46	18.46
UKC (Under Keel Clearance) $[m]$	7.04	7.04	7.04
y_{s3} (distance to the right bank) $[m]$	77.1	98.8,123.8,148.8,173.8	123.8
u_0 (initial ship speed) $[knots]$	5.0	5.0	5.0
n (propeller rate of turn) $[rpm]$	80	80	20,30,...,80

Table 3: Simulation parameters in different cases

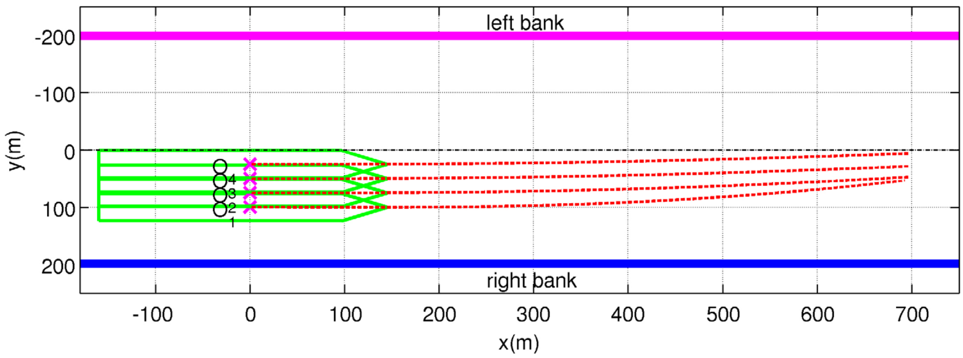

Figure 6: Ship trajectories with different ship-bank distances (case 1)

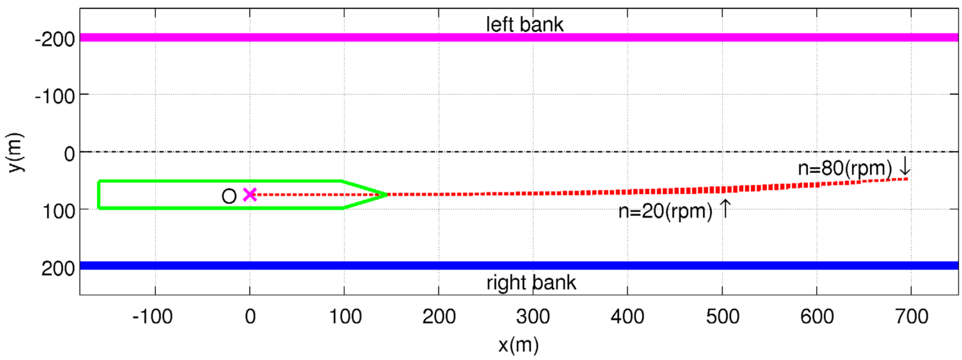

Figure 7: Ship trajectories with different propeller revolutions (case 2)

5 CONCLUSIONS

- The confinement model was successfully implemented into the maneuvering equations to simulate the ship navigating in the confined waterway.
- Small ship-bank distance and large propeller rate of turn can increase the confinement effect and influence the maneuvering of the ship.

REFERENCES

[1] M. Vantorre, "Experimental investigation of ship-bank interaction," in *Marsim03*, (Kanazawa, Japan), 2003.

[2] N. H. Norrbin, "A method for the prediction of the maneuvering lane of a ship in a channel of varying width," *Symposium on Aspects of Navigability of Constraint Waterways, including Harbor Entrances*, pp. 1–16, 1978.

[3] S. C. Ji, A. Ouahsine, H. Smaoui, and P. Sergent, "3-d numerical simulation of convoy-generated waves in a restricted waterway," *Journal of Hydrodynamics*, vol. 24, no. 3, pp. 420–429, 2012.

[4] S. C. Ji, A. Ouahsine, H. Smaoui, and P. Sergent, "3d numerical modeling of sediment resuspension induced by the compounding effects of ship-generated waves and the ship propeller," *Journal of Engineering Mechanics*, vol. 140, no. 6, p. 04014034, 2013.

[5] S.-C. Ji, A. Ouahsine, H. Smaoui, and P. Sergent, "3d modeling of sediment movement by ships-generated wakes in confined shipping channel," *International Journal of Sediment Research*, vol. 29, no. 1, pp. 49–58, 2014.

[6] F. Linde, A. Ouahsine, N. Huybrechts, and P. Sergent, "Three-dimensional numerical simulation of ship resistance in restricted waterways: Effect of ship sinkage and channel restriction," *Journal of Waterway, Port, Coastal, and Ocean Engineering*, vol. 143, no. 1, p. 06016003, 2016.

[7] D. Clarke, D. R. Patterson, and R. K. Wooderson, "Manoeuvring trials with the 193,000 tonne deadweight tanker "esso bernicia"," in *Spring Meeting of the Royal Institution of Naval Architects*, 1972.

[8] K. T. Tran, A. Ouahsine, H. Naceur, and K. E. Wassifi, "Assessment of ship manoeuvrability by using a coupling between a nonlinear transient manoeuvring model and mathematical programming techniques," *Journal of Hydrodynamics*, vol. 25, no. 5, pp. 788–804, 2013.